Diffractive J/Ψ Production and Proton Shape

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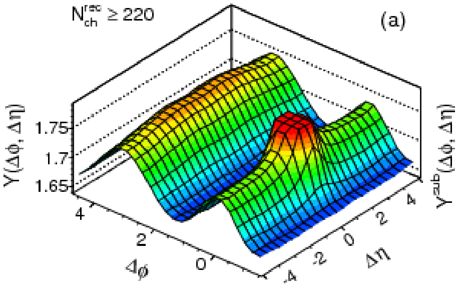
Based on: H.M., B. Schenke, PRL 117 (2016), 052301 and PRD 94 (2016), 034042, arXiv:1703.09256 and with B. Schenke, P. Tribedy and C. Shen, arXiv:1705.03177

A fundamental question

How are the quarks and gluons distributed in space inside the nucleon?

Practical applications

Initial state geometry is a necessary input for hydrodynamical simulations



ATLAS, arXiv:1409.1792

- Collective phenomena seen in pp&pA (v_n, mass ordering, ...)
- Initial state geometry
  $\Rightarrow$ final state collectivity

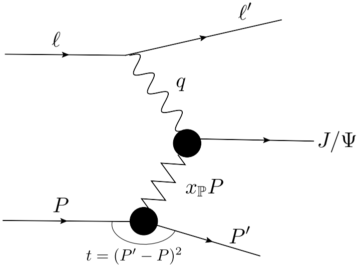
Diffractive processes probe

- Spatial density profile
- **Density fluctuations**

Workflow

1. Constrain event-by-event fluctuations of the proton structure from HERA diffractive DIS data
2. Model proton-nucleus and nucleus-nucleus collisions using the **constrained** proton geometry

Diffractive vector meson production



Diffractive events: no exchange of color charge

- Target remains intact: *coherent diffraction*, small $|t|$.
  Probes average distribution of gluons.
- Target breaks up: *incoherent diffraction*, larger $|t|$.
  Sensitive to fluctuations.

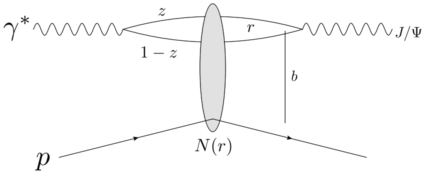
Target: proton or nucleus.

Exclusive process: experimentally t (conjugate to b) can be measured!

Diffractive vector meson production at high energy

Dipole picture at small x:

1. $\gamma^* \to q\bar{q}$ splitting: $\Psi^\gamma(r, Q^2, z)$
2. $q\bar{q}$ dipole scatters elastically: $N(r, x, b)$
3. $q\bar{q} \to J/\Psi$: $\Psi^V(r, Q^2, z)$



Diffractive scattering amplitude

$$\mathcal{A} \sim \int \mathrm{d}^2 b \mathrm{d}z \mathrm{d}^2 r \Psi^{\gamma^*} \Psi^V(r, z, Q^2) e^{-ib\cdot\Delta} N(r, x, b)$$

- Fourier transfer from impact parameter to transverse momentum Δ $\to$ access to spatial structure
- $\Delta =$ transverse momentum of the vector meson
- N is <u>universal</u> dipole-proton scattering amplitude (e.g. IP-Glasma)

Coherent diffraction = target remains intact

Target is at the same quantum sate before and after the scattering:
$\langle\rangle$ = target average (Miettinen, Pumplin, PRD 18, 1978, ...)

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to Vp}}{\mathrm{d}t} \sim |\langle \mathcal{A}(x, Q^2, t)\rangle|^2$$

with

$$\mathcal{A} \sim \int \mathrm{d}^2 b \mathrm{d}z \mathrm{d}^2 r \Psi^{\gamma*}\Psi^{V}(r, z, Q^2) e^{-ib\cdot\Delta} N(r, x, b)$$

- Coherent $t = -\Delta^2$ spectra is Fourier transfer of the **average density**

Incoherent diffraction = target breaks up

Total diffractive cross section − coherent cross section → target breaks up

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to V p^*}}{\mathrm{d}t} \sim \langle |\mathcal{A}(x, Q^2, t)|^2 \rangle - \left| \langle \mathcal{A}(x, Q^2, t) \rangle \right|^2$$

with

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- Incoherent cross section is variance ⇔ sensitive to fluctuations

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- Incoherent cross section is variance ⇔ sensitive to fluctuations

Constraints

Simultaneous description of coherent and incoherent data allows us to constrain the average shape and the amount of fluctuations

Constraining proton fluctuations

Start with a simple constituent quark inspired picture:

- Sample quark positions from a Gaussian distribution, width B_{qc}
- Small-x gluons are located around the valence quarks (width B_q).
- Combination of B_{qc} and B_q sets the degree of geometric fluctuations

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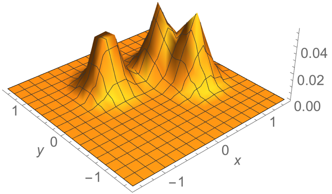
Now proton = 3 overlapping hot spots.

$$T_{\text{proton}}(b) = \sum_{i=1}^{3} T_q(b - b_i) \qquad T_q(b) \sim e^{-b^2/(2B_q)}$$



IP-Glasma model

- Use IPsat model fitted to F_2 data to extract $Q_s(b_T)$ from $T_{\text{proton}}(b_T)$
- Sample color charges ρ from distribution with variance $\sim Q_s(b_T)^2$
- Solve Yang-Mills equations to obtain the Wilson lines

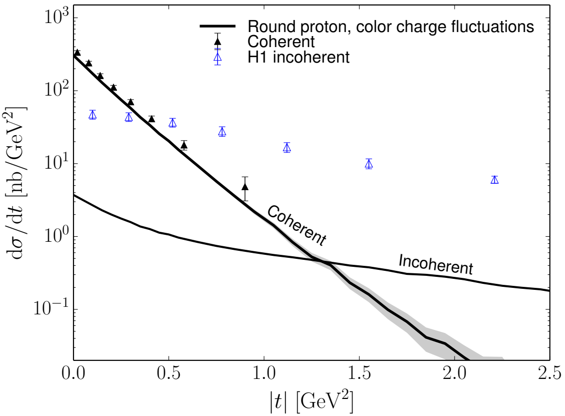
$$V(b_T) = P \exp\left(-ig \int \mathrm{d}x^- \frac{\rho(x^-, b_T)}{\nabla^2 + m^2}\right)$$

- Dipole amplitude: $N(x_T, y_T) = 1 - \mathrm{Tr} V(x_T) V^\dagger(y_T)/N_c$
- Fix parameters B_{qc}, B_q and m with HERA data

Wilson lines will be input for hydrodynamical calculations later!

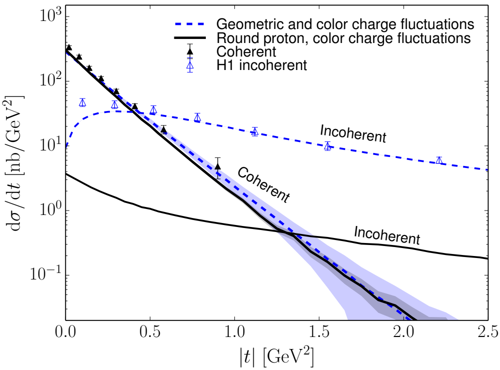
IP-Glasma and HERA data

$$\gamma p \to J/\Psi p, W = 75 \text{ GeV } (x \sim 10^{-3})$$

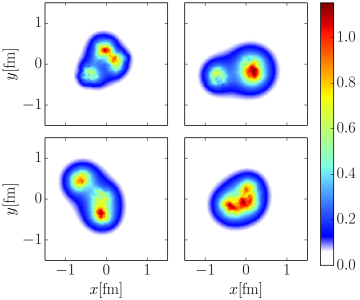


- Color charge fluctuations alone are not enough

IP-Glasma and HERA $\gamma p \to J/\Psi p$ data



Parameters fitted to H1 data



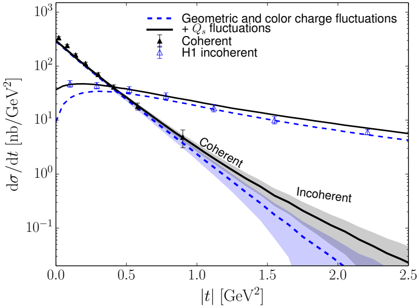
H.M., B. Schenke, PRD94 (2016), 034042

- Large geometric fluctuations (at $x \sim 10^{-3}$) are needed

Saturation scale fluctuations

McLerran, Tribedy, 1508.03292: $p+p$ multiplicity fluctuations suggest:

$$\text{Quark } Q_s \text{ fluctuates as } P(\ln Q_s^2/\langle Q_s^2\rangle) \sim \exp\left[-\frac{\ln^2 Q_s^2/\langle Q_s^2\rangle}{2\sigma^2}\right]$$

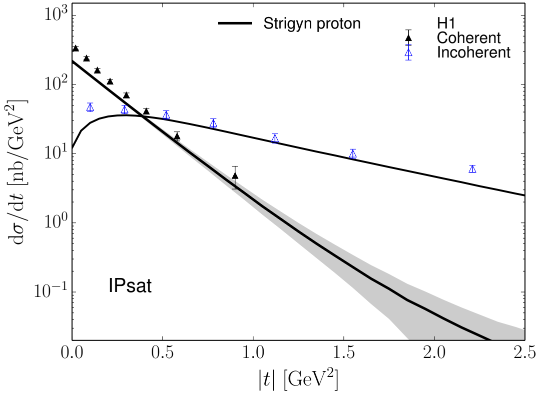


Effect of Q_s fluctuations

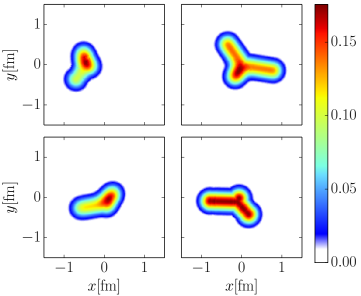
Q_s fluctuations are long-distance effect, and dominate at small-t

Lumpiness matters, not details of the density profile

Example: 3 valence quarks that are connected by "color flux tubes": Also a good description of the data with large fluctuations



Example density profiles



Here using IP-sat model to describe dipole-proton scattering

H.M, B. Schenke, PRD94 034042
Flux tubes implementation following results from hep-lat/0606016, used also e.g. in 1307.5911

Application I: collectivity in pA collisions

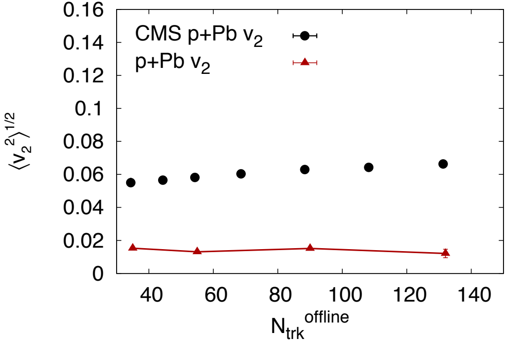
Large elliptic flow (v_2) seen in pA collisions

IP-Glasma with hydro works will with the AA data, apply to pA
Does it work?

First approach: round proton with only color charge fluctuations

B. Schenke, R. Venugopalan,

PRL113 (2014) 102301



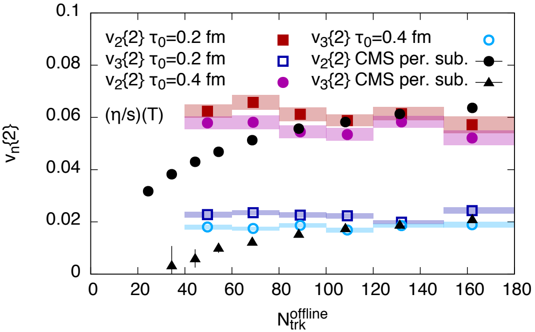
Color charge and Q_s fluctuations in the initial state do not create large enough flow harmonics to the final state

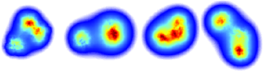
Hydro calculations with proton fluctuations from HERA

Hydro numbers
(results insensitive to these)

- $\tau_0 = 0.2 \ldots 0.4$ fm
- $T_{\mathrm{fo}} = 155$ MeV
- Shear and bulk viscosity
- Initial $\pi^{\mu\nu}$
- $\eta/s = \eta/s(T)$ or $\eta/s = 0.2$

Good description of v_n at high multiplicities.

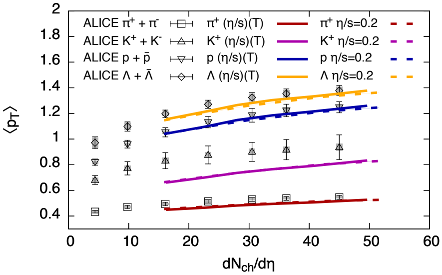


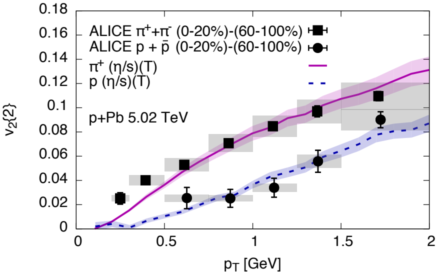


H.M, B. Schenke, C. Shen, P. Tribedy,

arXiv:1705.03177, data: 1305.0609

Application I: collectivity in pA collisions



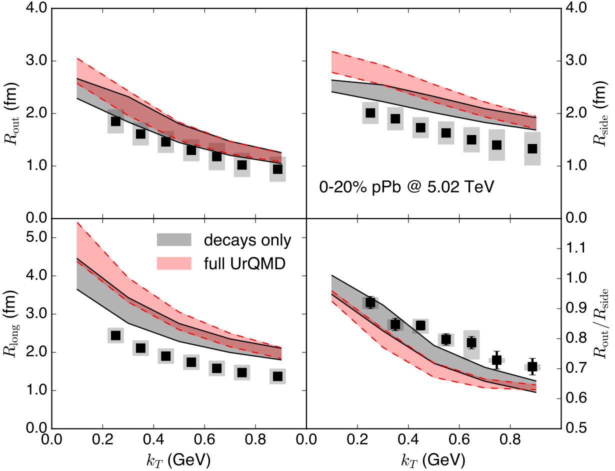


- Centrality and p_T dependence for identified hadrons in good agreement with ALICE data
  - Especially bulk viscosity is necessary to get $\langle p_T \rangle$

H.M, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177, data: ALICE 1307.6796

Application I: collectivity in pA collisions

Also OK description of the ALICE HBT radii data

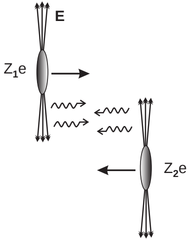


H.M, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177, data: ALICE 1502.00559

Application II: Ultraperipheral AA collisions

UltraPeripheral heavy ion Collisions (UPC):
access to nuclear DIS before an EIC

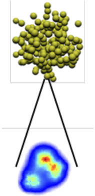
- At $|b_T| > 2R_A$ one nucleus acts as a photon source
- Write dipole-nucleus amplitude N_A as



$$1 - N_A(r_T, b_T, x) = 1 - \prod_{i=1}^{A} \left[1 - N(r_T, b_T - b_{T,i}, x)\right]$$

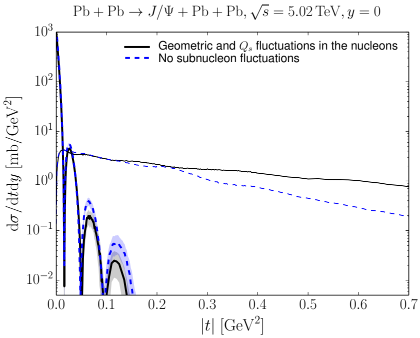
Two sources of fluctuations:

- Sample nucleon positions from Woods-Saxon
- Sample constituent quark structure for each nucleon



Currently: no IP-Glasma description of the nucleus, use IPsat to describe dipole-nucleon scattering

Accessing fluctuations at different scales



Coherent: thick lines

Incoherent: thin lines

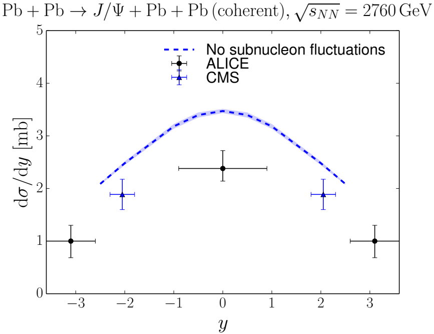
H. M., B. Schenke, arXiv:1703.09256

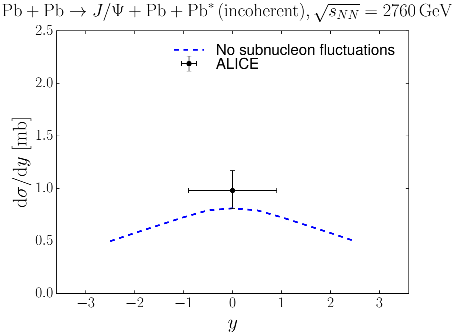
- $\sqrt{|t|}$ is conjugate to b_T
- Small $|t|$: fluctuations of nucleon positions
- Large $|t|$: fluctuations at subnucleon scale
- Incoherent slope changes at

$$|t| \approx 0.25\mathrm{GeV}^2 \sim 0.4\,\mathrm{fm}$$

  which is size of hot spots
- Midrapidity $Au + Au$ data from RHIC at $\sqrt{s} = 200$ GeV probes $x \sim 10^{-2}$

Comparison to LHC data, no subnucleonic fluctuations

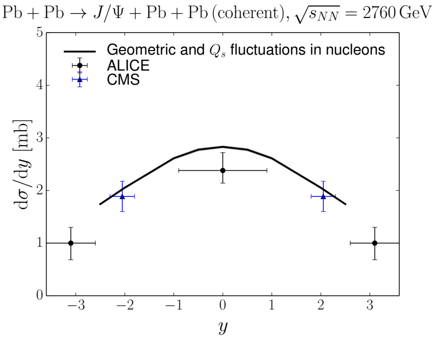


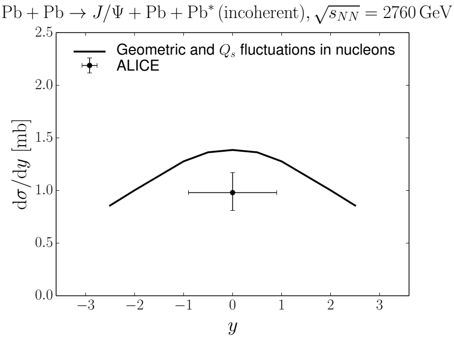


- Only fluctuations of nucleon positions from Woods-Saxon: Coherent cross section overestimated and incoherent underestimated
- Large overall normalization uncertainty from the J/Ψ wave function

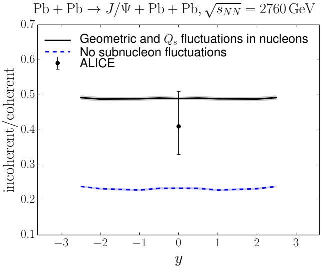
H.M, B. Schenke, arXiv:1703.09256

Comparison to LHC data, with subnucleon fluctuations



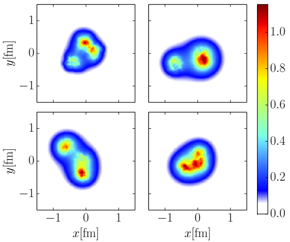


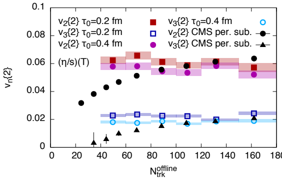
- Consistently slightly above the data, incoherent/coherent ratio compatible
- Model uncertainties (e.g. J/Ψ wave function) mostly cancel in cross section ratio

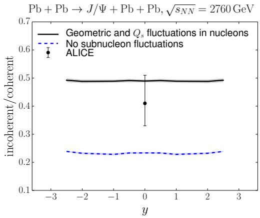


Conclusions

- Constrain (amount of) proton structure fluctuations using HERA diffractive data
- Applications to LHC
  - pA hydro calculations compatible with LHC v_n data
  - Effect of subnucleonic fluctuations visible in ultraperipheral AA Incoherent t spectra $\rightarrow$ scale at which fluctuations take place
- Outlook: EIC will make it possible to study A and x dependence of the fluctuating structures
- Next step: include small-x evolution in terms of JIMWLK equation







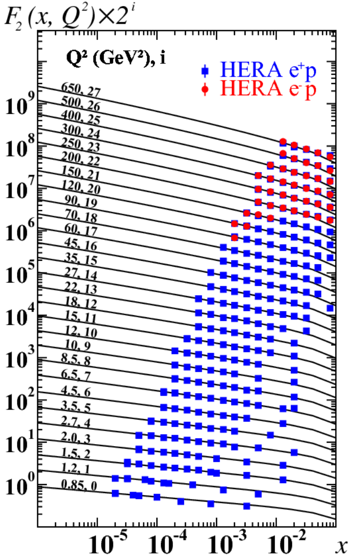
Backups

Dipole-target scattering: IPsat

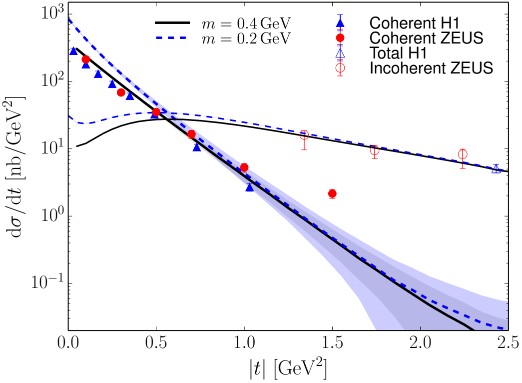
Impact Parameter dependent saturation model for the dipole amplitude

$$N = 1 - \exp\left[-\frac{\pi^2}{2N_c}\alpha_s xg(x,\mu^2)\,T_p(b)\,r^2\right]$$

- $T_p(b)$ is transverse proton density function (Gaussian)
- xg is DGLAP evolved gluon density
- Free parameters fitted to HERA F_2 data
  (Kowalski, Teaney 2003; Rezaeian et al, 2013)



Insensitivity on infrared cutoff

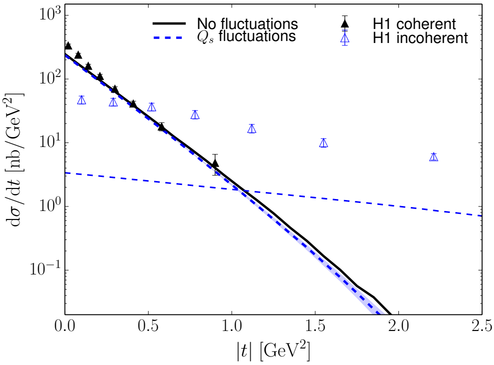


IP-Glasma: IR cutoff $m \sim \Lambda_{\mathrm{QCD}}$ to regulates long distance coulomb tails

- Proton size depends on m
- No sensitivity at large $|t|$

Saturation scale fluctuations w/o geometric fluctuations

Allow Q_s^2 to fluctuate, $P(\ln Q_s^2/\langle Q_s^2\rangle) \sim \exp(-[\ln^2 Q_s^2/\langle Q_s^2\rangle]/2\sigma)$
Constrained by *pp* multiplicity fluctuations (McLerran, Tribedy, arXiv:1508.03292)



- Q_s fluctuations alone are not enough